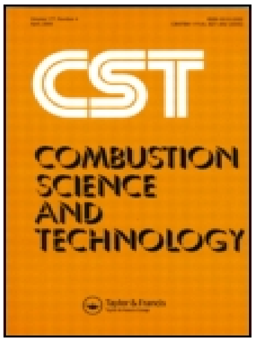

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The Further History of Fire Science

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Presented at the Fire Research Conference in honor of Howard Emmons, Washington D.C., 1983

I begin this "History of Fire Science"† three hundred years ago in the middle of the twentieth century. I choose this starting date because by then there was a well developed public awareness of the seriousness of fire and a procedure of city fire codes and variously approved tests and standards. To be sure, these were almost entirely empirical but the realization of the importance of developing a fundamental understanding of fire through the methods of science was developing and the computer, then in its infancy, was making quantitative fire theory possible.

It is hard for us today to realize the state of society's fire problem in that early time. Of course, today we are shocked when any significant fire occurs, especially if anyone is killed. In the twentieth century hardly a day went by without reports of serious fires in nearly every city. And thousands of persons died in fires every year.

At that time fire safety, such as it was, was controlled through city building codes by specifying what must and must not be done. They were *specification* codes, obviously less than adequate. The first *performance* fire codes were not enacted until the year 2000 which was as soon as the knowledge of fire and the accumulated empirical fire data made general building fire predictions sufficiently accurate.

By the middle of the twentieth century, the classical dynamics, the classical quantum chemistry, and the computing machinery had all progressed to the point that solutions of the simpler problems of fire science first became possible. Large numbers of plastics and other new materials were being used in furniture, furnishings and appliances. Many of these materials were made from the then plentiful natural petroleum supplies. These were all highly flammable unless fire retarded, and many fire retardants, the halogens, phosphates, ammonium brought pyrolysis or fire product problems with toxic gases.

Asbestos had just been found to be carcinogenic and the innumerable noncombustible mineral-based rigid and flexible foamed materials so common today had not yet been discovered.

The nature of chemical reactions, stoichoimetry and thermodynamics were well developed, but chemical kinetics was then a frontier research field. While the quantum mechanics of the day could solve such problems "in principle" it was completely inadequate to say anything useful for fire science. Thus the meager understanding of pyrolysis and combustion was essentially wholly empirical. The fire codes of the day specified various so called flammability tests as though flammability were a material property rather than a system property. It is no surprise that small scale flammability tests were notoriously poor simulations of real fires and that larger scale tests, corner tests or room tests, were at best only fire models of limited applicability.

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† The Development of Fire Science from the dawn of history to 1980 was briefly reviewed in a paper presented at the symposium in honor of the contributions of Philip Thomas (see Emmons, 1981).

By 1980 it was already known that dynamics controlled large parts of fire development. Elementary cases of various component problems had already been solved in a practical way. The free plume without combustion, the hot layer development, the forced and buoyant flow through vents, had workable solutions using suitable empirical coefficients to cover viscous and turbulent effects not included in the practical theory. In fact the appropriate physical laws and their embodiment in multicomponent flow equations was complete but turbulence was still an unsolved problem so that the coefficients in the practical theories, while computable "in principle", were not computable in fact.

Radiation heat transfer was known to be the dominant mode of energy feedback in fire spread in large fires. In fact, the knowledge of interaction of radiation and matter was sufficiently advanced to compute radiative transfer to high precision if the chemical specie, temperature, and pressure distributions were known. However, essentially nothing was known about the statistical properties of flames, even empirically. Even mean properties of flames had been measured only under such limited circumstances that only the crudest guesses could be made for a real fire. Flames were, for theoretical purposes, usually cones or cylinders of uniform temperature and emissivity, neither of which could be known with any precision for a given burning plastic in a vitiated atmosphere of known composition. And, in fact, generally neither the material nor the ambient conditions were known very accurately.

Although the toxic products of incomplete combustion were known to be the primary cause of death from fire, the knowledge of both the production and transport of toxic gases and the details of their physiological effect was in a most elementary state. There were still basic arguments on how the material should be pyrolysed or burned, on whether mice or rats should be the test organism, on whether leg flecture or wheel rotation should be the preferred test method. Nothing had been done with the real fire effects of composite materials and no information was available on how the toxic property of fire gases changed as the gases accumulated at the ceiling, burned and flowed out the door and eventually into an escape route.

By the 1980's, the limitations of the available fire test methods were known, corner tests and room tests had begun to be used, and there was discussion of what new types of tests were needed. It wasn't until 1995, however, that the first test method capable of supplying rate of fire spread, rate of pyrolysis and crude composition data (CO_2, CO, C, H_2O, H_2, $(CH_2)_x$) for pyrolysis, smoldering, and flaming combustion became generally available. These tests included control of external radiation but not much control of atmospheric vitiation.

Thus the practical math modelling of fires which was begun in the late 1970's and had by 1990 been fully extended in a practical way to a multi-story building was not yet capable of supporting a performance code because of the absence of adequate empirical data on items of furniture. The computer codes were under rapid development and they were used for various research purposes and in occasional fire litigation.

It was clear by the year 2000 that there would be a need for many special purpose, practical computer codes as well as a high precision code. The practical computer codes were then, as is still true today, crude zone models of sufficient accuracy to their designed purpose. Only the high precision code continued to be improved with the latest and best information.

The practical codes were of very limited use because of the limited empirical data available while the precision code was limited by both the available data and the computing capacity of the then best computers.

The 4th quarter of the 20th century was a period of impressive progress on the component phenomena on fire. This was a necessary preliminary since without an adequate quantitative understanding of the building blocks of a fire, the overall fire phenomena itself could not be put together.

Fire growth models on solids including pyrolysis, smoldering, flame spread, and charring were developed so that empirical data on various materials could be organized in a useful, predictive way. This work was essential to the practical zone models of fire. However, the lack of detailed knowledge of the thermal decomposition and combustion chemistry made sufficiently accurate quantitative predictions of fire growth, combustion, and gas toxicity impossible.

In spite of the basic difficulties, great progress was made toward understanding fire growth. Fuel surfaces in the horizontal (floor), vertical (wall) and horizontal (ceiling) positions were all studied. Essential empirical data correlations made predictions possible using numerous empirical coefficients. The most important contribution was the development of adequate theories to predict the performance of charring materials which included most of the plastics then in use as well as nature's plastic, wood.

The ignition and burning of the vitiated fire gases at the ceiling of a room and in flames emitted at a vent was empirically clarified and made predictive. In addition, the occurrence of air flames near the floor emitted at a vent into a fully ventilation controlled room fire had been discovered and shown to behave just like the out flowing flames at the top.

Since radiation is the principal energy feedback mechanism, extensive work was being done on soot production. Much essential progress was made but the complexity of the chemical kinetics and its interaction with the fire dynamics—turbulence and radiation—prevented useful quantitative predictions. This knowledge, however, suggested the method of defining a soot coefficient and its correlation which provided the empirical basis of useful soot predictions.

As progress was made with soot predictions, more accurate predictions of radiation from both diffusion and premixed flames was possible. These improvements were used in the precision computer code but the practical codes usually used simplified approximations.

Although the precision code and some of the practical codes continued to use computed view factors, the most popular codes, good enough for many design purposes, used the method of a radiation rate pool. This method, developed in a useful form about 1990, supposes all radiation from all bodies to be put into a pool and then sent to all bodies in proportion to their surface area. While this method is of low accuracy, it has been found to produce errors of the same order as the permitted practical variations in the flammability and location and number of items of furniture and appliances. This method is no longer used today since the modern city fire codes require an accounting of and limitations on the permitted fire load in public buildings and the fire index on all purchased items permits each householder to limit the residence flammability. And, of course, the penalties for having a residence fire make enforcement practical.

The practical understanding of plumes without flames was completely developed before the year 2000. Extensive practical theory and measurements for free plumes, plumes by walls, plumes out of vents, plumes by beds and under tables, etc. had all been studied and reduced to reasonably accurate predictive methods.

Although several attempts had been made to develop a plume theory with a flame, the problem was so intimately tied to chemical kinetics, turbulence, and radiative interchanges that a practical result was not attained until 2020. In the meantime, cruder approximations had to be used. These were of the form of an empirical rate of heat release which for plume calculations was assumed to occur on the fuel surface.

The related problems of ignition, extinction and suppression were given a lot of attention near the end of the twentieth century. While a great deal of essential basic work on these problems, especially sprinkler systems, was performed, it gradually became clear that chemical kinetics played an essential role and therefore really basic solutions were blocked by the chemical complexity and the inadequacy of the underlying quantum chemistry.

During this same period, the work on toxicity moved out of its little smoke oven for testing single materials into the larger problem of predicting the safety from fire gases in distant escape routes. The obvious idea of following the history of every known toxic compound throughout a building was being challenged by the idea of defining a toxicity index for the fire gases and following its increases and decreases as the gases move about and react. By the close of the twentieth century almost nothing had been done with the physiological effects of fire toxicants and without this knowledge the various contentions between toxicologists could not be resolved.

We can view the years 1950 to 2000 as the period in which the basic ideas of fire science were developed, in which the essential fire components were all identified, and their fundamental character clarified. The necessity of basing public fire safety on performance fire codes evaluated through predictive computer fire codes was recognized and the first steps of implementation were taken. Methods of solving 3D fire problems had been developed but were not used outside of an occasional research project because the available computers were too slow and too small to put such calculations within reach of most budgets.

The computer was limited by the size of the basic switching unit which was about 10,000 Å and the required power posed a serious heat transfer problem. In fact, the principal progress during the 1990's was in parallel computing, thus providing a basic computing speed of only about 10^9 calculations per second.

The fire record had continued to improve during this period, however, with minimal help from the science. Experience continued to point the way toward better specification codes, better, more realistic tests, and better methods of enforcement in new building construction. But the real improvements awaited the practical use of performance codes.

The 21st Century

The advent of city performance fire codes ushered in a new era. The 21st century opened with fairly good practical computer fire codes whose most serious limitation was the paucity of fire data on furnishings. The necessity of passing such city codes, however, forced industry to pay for the testing of its products just as had occurred with the tunnel and other tests in the preceding century. Thus the practical computer codes became more powerful rather rapidly during the first quarter of the century.

Science and fire science in particular continued to struggle with turbulence and chemical kinetics making small gains here and there without providing any great improvements in the precision fire code. Since the precision code was not much improved, a great deal of test work, especially with full scale buildings was needed to validate the many practical codes.

The heart of the problem of practical performance codes is the ability to predict the safety of the occupants and the extent of the fire damage when a proposed new building is in the design stage. Clearly only a very powerful computer can include all the complex geometric, physical, and chemical interactions which are critical to fire growth.

The required predictions are of four kinds:

1) The time of response of fire detectors warning all occupants of the emergency.

2) The time history of temperature and toxic gases in all escape routes.

3) The property loss by direct fire destruction.

4) The property loss by soot and absorbed odors of fire gases.

For many years the early performance codes considered only occupant safety. But just this part of the fire safety problem requires a knowledge of most of the science of fire. The feedback energy produces more fire gases of course. If the fuel is a liquid or subliming solid, the fire gas flux is produced by a heat of vaporization and is easily calculated because the fuel surface temperature is known. For a charring solid or complex fluid the surface temperature and heat losses are not known and some chemical rate relation must also be used simultaneously with the thermal and dynamic surroundings.

To supply this detailed basic data to the computer required very extensive empirical testing and data correlation work. A large body of empirical chemical kinetic data had to be measured. Unfortunately the nature of the products of a fire are highly variable with local availability of oxygen and thus much effort in the first half of the 21st century was required to build the computer fire data bank.

The flow of fire gases through a large building involves buoyant, turbulent flow through doors and windows, through rooms and down corridors. The speed of sound is so high, that pressure transients are essentially instantaneous on the scale of fire development. Thus in the absence of buoyancy, the flow-pressure relations are a succession of steady states. The buoyancy on the other hand makes Froude number transients important almost everywhere. The simple hydraulic loss coefficients and friction factors of non-buoyant flows are no longer directly applicable but must be considerably modified to predict buoyant driven transients. It was well into the 21st century before these effects were fully appreciated and the appropriate coefficient measured.

The questions of predictions of building collapse were not even considered until about 2020. This is understandable because of both the extreme complexity of the thermal structural problems and the fact that the occupants are long since removed to safety or dispatched by the fire and the building is already nearly worthless. However, the prediction of collapse is important for the prediction of the safety of firemen. Thus it wasn't until 2050 that enough thermal structural theory was added to the fire predictive program to make it possible for the fire chief to receive backup computed information to aid him in his critical decisions with respect to the safety of his men.

That the spectral properties of fire radiation was important was known from the very beginning of fire science. However, the use of such knowledge was not justified when the temperature, composition, position, and size of flames were so poorly known. As the knowledge of flame dynamics improved, the spectral properties of flame radiation was reexamined. Since soot is the major source of fire radiation and most materials char at fire temperatures, most fire radiation is reasonably approximated as grey—nearly black. Where spectral properties are important is in fire tests. The common and convenient method of applying external radiation in a fire test is by electrically adjusting the temperature of a radiation source. However, this not only adjusts the intensity but also the spectral distribution which may not be desirable.

New relatively cheap, high precision chemical analysis equipment began to appear in fire test methods about 2010. Thus adequate empirical data on the chemical nature of the emissions during pyrolysis, smoldering and burning became available. Thus the inevitable excess pyrolisate of a fire could be accurately quantified and test methods using vitiation control were soon developed. Thus the ground was laid to provide all the empirical fire data needed for practical fire predictions required by city performance fire codes.

The first major breakthrough in fire safety was brought on by the rising price and dwindling supply of petroleum. Oil shale, and synthesis from coal and agricultural wastes, were important but the day of the cheap petroleum based plastics was at an end. Thus numerous attempts to produce an all mineral cellular plastic flexible or rigid, began to pay off. The first such material appeared in 2025 and was rapidly followed by numerous others.

The second breakthrough came in 2030 when the efforts to make an all optical computer switching unit smaller and with less energy requirement succeeded. Thus followed the second rapid revolutionary computer development. We note that the first rapid growth phase that followed the invention of the transistor in the 1950's had slowed almost to a stop by the year 2000. The new optical units gradually over a 50 year period decreased the size of the basic switching unit to 100 Å, a decrease of 100. Thus the area packing increased by 10,000. But, more important, the great decrease in power requirement alleviated the serious heat transfer problems so that now the unit stacking was not limited to a surface but units could be built up in volume. Thus the powerful computers of today a factor of 10^6 smaller for a given computing capacity and 10^8 faster were available by 2080.

During the 50 years 2030–2080 the theoretical foundations of fire science were completely revamped. At the beginning of this period through various semi-empirical approximations, both some turbulence and some chemical kinetics could, in principle, be solved. As the computing power improved more and more of these problems could be solved in fact. Thus gradually it became possible to understand and compute many of the previously empirical coefficients. Plume mixing coefficients and various vent and corridor flow coefficients could be computed more accurately than they could be measured. The flame in a plume and the hot layer burnout could be predicted using both 3D turbulence models and the detailed chemical kinetic specie predictions.

Thus the precision fire code began to be used as a validation of various new special purpose practical codes. The precision code incorporated various of the 3D component calculation methods but the computation cost then as now does not justify its use in practical work.

As the demands for fire predictions by performance codes grew and the knowledge of fire behavior in general improved, the toxicity testing was greatly expanded. Physiological work clarified many of the short term and long term effects of fire gases. It also showed why various synergistic effects occurred. This knowledge made it possible to introduce new and faster test methods and to learn how best to use the results.

On test methods, both mice and rats were replaced by a series of bacteria and special chemical tests. By proper selection, many of the physiological effects in humans could be separately evaluated in real time. Thus enormously important new data previously unattainable could be measured in real fires.

The method of use by following the history in a fire of all known toxic substances was too complex for practical use. The contention that a toxicity index could be used in fire predictions proved to be too inaccurate. Gradually between 2030 and 2040 it became clear that a few specific chemical specie, notably CO, HCN, HCl, $CH_2=CHCHO$ had to be followed in detail but that the toxic effects of the vast array of organic materials beyond these few that are present in fire gases can be adequately treated using a toxicity index.

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The 22nd Century

The third great breakthrough occurred in 2110. New insights, new mathematical methods and a really powerful computer finally opened the way to a complete understanding of turbulence. Not only did this development validate many of the approximate methods already in use but disclosed their often unexpected limitations. The new methods were sufficiently simple to put all fire dynamics problems within reach of the precision code but much of that code continued to use the approximate methods now shown to be of high precision.

The 23rd Century

The fourth great breakthrough was the discoveries and simplifications in quantum chemistry in 2200. This did for chemical kinetics what had been accomplished for turbulence. Much of the huge computer compilation of pyrolysis, smoldering and burning data for materials could be directly verified by computation. The computation of many chemical kinetic problems of solids and liquids are still too complex to warrant the replacement of the computer stored fire data for material by a basic quantum calculation. However, such calculations are most useful to fill out missing data in the file and for supplying the data appropriate to new combustable materials as they were introduced.

The demise of cheap petroleum and the discovery of many replacement mineral based products during the 21st and 22nd centuries has greatly reduced the problem of fire in society. By the 23rd century fire dynamics and chemistry were so advanced as to be no longer exciting research fields. However, the physiology of toxic fire gases is still in need of further study. Practical predictions of the toxic conditions in escape routes are usually good enough for building design purposes. However, every now and then a fire does occur and in a few of these cases the toxicity prediction is not as good as it should be.

As we look back we see that the 20th century saw the clarification of the basic effects of all component fire phenomena. Also the first practical computer fire codes came into use and an elementary precision code had been started. The 21st century was the period when the basic empirical thermal, chemical and physical data on materials, furniture and furnishing became fully supplied. The premier development of mineral based cellular materials occurred and the computer development was nearly complete. Finally the 22nd century advanced turbulence and quantum chemical kinetics knowledge to the state that most required fire knowledge could be computed from first principles so that little empirical testing was any longer necessary. And finally the 23rd century saw the toxicological knowledge reach its practical limit although many physiological problems remain for ultimate solution in the present 24th century.

Thus by the present year, 2300, we inherit a great engineering development which assures us of a nearly fire free life. As we look back at the developments, many of them could have been available decades before they actually appeared if only society through governments had understood the scientific process as it developed fire science and supplied the funds required to carry out the work which was at the time known to be necessary.

No one can predict the impending occurrence of a major revolutionary advance but progress could have been many times faster between such advances if only a minute fraction of the funds spent on other societal problems were used to advance fire science.

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